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Surface thermal perturbations of the recent past at low latitudes – inferences based on borehole temperature data from Eastern Brazil

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Abstract

Borehole temperature data from the eastern parts of Brazil has been examined in an attempt to extract information on surface thermal perturbations of the recent past at low latitudes. Forward models were employed in the analysis of temperature logs from 16 localities and, in addition, inverse modeling was carried out for data from 10 selected sites. The model results have allowed determination of the magnitude as well as the duration of ground surface temperature (GST) changes in three major geographic zones of Brazil. Prominent among such events are the warming episodes that occurred over much of the subtropical highland regions in the southeastern parts of Brazil. The present magnitude of GST changes in this region are in the range of 2 to 3.5°C but have had their beginning during the early decades of the 20th century. Nearly similar trends are also seen in temperature-depth profiles of bore holes in the subtropical humid zones of the interior and coastal areas of southern Brazil. The data from semi arid zones of northeast Brazil also indicate occurrence of surface warming events but the magnitudes are in the range of 1.4 to 2.2°C while the duration of the warming event is larger, extending back into the last decades of the 19th century. There are indications that changes in both climate and vegetation cover contribute to variations in GST. Thus the magnitudes of GST variations are relatively large in localities which have undergone changes in vegetation cover. Also there are indications that GST changes are practically insignificant in areas of tropical rain forest. Another important result emerging from model studies is that the climate was relatively cooler during the 17th and 18th centuries. The climate histories, deduced from geothermal data, are found to be consistent with results of available meteorological records in southern Brazil. Comparative studies also indicate that the magnitudes and duration of recent climate changes in southern and eastern Brazil are similar to those found in other continental areas such as North America, Asia and Europe.

1 Introduction

Geothermal methods have been employed during the last few decades for extracting information on climate changes of the recent past in several regions of the northern hemisphere (Birch, 1948; Cermak, 1971; Beck, 1977; Lachenbruch et al., 1982; among others). Nevertheless, very few attempts have been made in using geothermal data for examining climate variations in low latitudes of the southern hemisphere. Among the earlier efforts in this category are the studies carried out in Australia (Cull, 1979, 1980), Brazil (Hamza, 1991; Hamza et al., 1991; Hamza, 1998) and South Africa (Tyson et al., 1998). Since 1980 a number of studies have been carried out for examining climate variations of the recent past in several regions of Brazil. However, much of the recent works remain as publications of limited access, such as internal reports (Hamza et al, 1978; Eston et al, 1982; Hamza et al, 1987), academic thesis works (Vitorello, 1978; Araújo, 1978; Santos, 1986; Ribeiro, 1988; Del Rey, 1989; Cavalcanti, 2003) and proceedings of local meetings (Ribeiro, 1991; Souza et al., 1991; Cavalcanti and Hamza, 2001; Cerrone and Hamza, 2003; and Conceição and Hamza, 2006). In the present work we provide a synthesis of some of these recent works, with emphasis on the results discussed by Hamza and Cavalcanti (2001) and Cavalcanti (2003).

As prelude to the discussion of results presented in this work, relevant for analysis of climate changes of the recent past, we provide first a brief description of the prevailing climate patterns, which have direct influence on the ground surface thermal budget of the study area. Following this, the background information on the sources and characteristics of geothermal data base are presented and the criteria used for data selection outlined. Details of the forward and inverse methods used for extracting information on past climate are set out in the next section. The results obtained in model simulations of temperature-depth profiles are classified into groups representative of the major geographic zones. Finally, the climate history of Brazil deduced from geothermal data is compared with results of meteorological records of the last century and also with climate patterns observed in other continental areas.

2 Prevailing climate zones

Three main climate zones may be recognized in the continental region of Brazil: tropical (or Equatorial), Sub-Tropical and Semiarid (INMET, 2003). The Equatorial climate pattern prevails in the northern and northwestern parts of the country and includes both highlands and plains. The average temperatures are in the range of 24 to 26°C while precipitation runs in excess of 2500 mm/yr. The vegetation cover presents considerable variability depending on the altitude and soil type. Nevertheless, some general patterns may easily be recognized. For example, the vegetation cover is exuberant in the Amazon region while it is markedly less intense in areas outside the region of tropical rain forest. The climate pattern of northeast Brazil is better described as semiarid. The average temperatures are in the range of 25–29°C, with amplitudes of annual variations of slightly over 5°C. The precipitation is less than 800mm/yr and consequently the vegetation cover is scanty, being mostly shrub type.

The Subtropical climate pattern prevails in areas to the south of the Tropic of Capricorn where the temperatures are less than 20°C and amplitudes of annual variations are in the range of 9° to 13°C. The precipitation rate is in the range of 1500 to 2000 mm/yr. The type of vegetation cover depends on the soil type and altitude. The high land areas in the southeastern and southern parts are characterized by mean temperatures in the range of 18° to 22°C. The amplitudes of annual variations are in the range of 7° to 9°C. The summer seasons include intense rainy periods while cold front excursions advancing from the South Polar Region are frequent in the winter season. This type of climate is found frequently in the highland areas in the east as well as areas situated in the southern state of Paraná and in the southwestern state of Mato Grosso do Sul. The vegetation cover is mainly dense in areas of subtropical forests. The Pantanal Complex in the west-central parts of Brazil is characterized by forests with mixed species of vegetation, pockets of rain forest and semi-arid areas. The diversity in vegetation cover is believed to arise from the frequent shift between dry and rainy seasons.

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The Atlantic subtropical climate pattern is found along the coastal areas in the east, south of the equator. The mean temperatures are in the range of 18° to 26°C, but the amplitudes of temperature variations increase from north to south. The mean value of precipitation is over 1200 mm/yr but its distribution is highly variable. It is mainly during the winter in the northern parts and during summer in the southern parts. The original vegetation cover of the coastal areas (frequently designated as Atlantic Forests) has undergone substantial changes during the last century, as a result of large scale human occupation, modern developments in land use and intense agricultural practices. At present, the original Atlantic Forest is preserved only in some isolated and scattered sectors, which together constitute less than 10% of the coastal area.

The area extent of the main climate zones and some of their subdivisions are illustrated in Fig. 1. Detailed climate maps of Brazil are available at the websites of the National Institute of Geography and Statistics – IBGE (http://www.ibge.org.gov.br) and the National Institute of Meteorology – INMET (http://www.inmet.org.gov.br).

3 Characteristics of the data base

According to the recent compilations carried out by the National Observatory (Observatório Nacional – ON/MCT) geothermal measurements has been carried out in 434 localities in Brazil (Hamza et al., 2005). Most of the earlier data were acquired as parts of basic research projects for heat flow determinations and also as parts of applied research projects for oil exploration and geothermal energy assessments. The focus of data acquisition in the earlier works has been on determining temperature gradients in the deeper parts of the borehole.

The characteristics of these data sets are variable, depending on the method used for primary data acquisition. Of these, only the one acquired using the so-called conventional method (CVL) provide direct information on the vertical distribution of temperatures at shallow depths and hence potentially suitable for climate related investigations. This method has been employed for geothermal studies in 129 localities, which is slightly less than 30% of the overall data set. It includes mainly temperature logs in bore holes and wells and thermal property measurements on samples representative of the local geologic formations. In some cases estimation of radiogenic heat production was also carried out. The details of the experimental techniques employed for temperature and thermal conductivity measurements have been discussed in several of the academic thesis works (Vitorello, 1978; Araújo, 1978; Del Rey, 1989; among others) and in publications dealing with heat flow measurements (Hamza et al., 1987; Hamza and Muñoz, 1996; Gomes and Hamza, 2005). A direct evaluation of the quality of data acquired in the earlier works is a difficult task since the experimental techniques used for temperature and thermal conductivity measurements have undergone substantial changes over the last few decades.

The sources of conventional (CVL) data set employed in the present work may be considered as falling into the following three main groups:

1. That acquired during the decade of 1970 in the southern and eastern parts of Brazil. Most of this data has been published in the Brazilian Geothermal Data Collection – Volume 1 (Hamza et al., 1978). Some of these data were used in academic thesis works of the late 1970s (Vitorello, 1978 and Araújo, 1978) and related publications Vitorello et al., 1978; Hamza, 1982);

2. That acquired during the decade of 1980, mainly in the state of São Paulo, as parts of hydrocarbon and geothermal energy exploration programs. Some of these data were reported as parts of academic thesis works of the 1980s (Santos, 1986; Ribeiro, 1988; Del Rey, 1989) and related publications (Santos et al., 1986; Del Rey and Hamza, 1989);

3. Recent data acquired since the year 2000, mainly in the state of Rio de Janeiro and neighboring areas. Some of these has been employed in geothermal climate change studies of the state of Rio de Janeiro (Cerrone and Hamza, 2003; Hamza et al., 2003) also in mapping heat flow variations in the coastal area of southeast Brazil (Gomes, 2003; Gomes and Hamza, 2005).

4 Selection criteria for climate studies

The characteristics of the conventional (CVL) data set were examined carefully to screen out possible perturbations arising from non-climatic effects. Thus, data acquired at shallow depths less than 20 m were excluded from analysis of climate changes, avoiding thereby eventual perturbing effects of diurnal and seasonal variations in the reconstruction of surface temperature history. Also, local temperature distributions are likely to be perturbed by such non-climatic factors as topography and groundwater flow. In addition, it was necessary to eliminate those which do not provide fairly reliable determinations of both the steady and the transient components of the subsurface thermal field. In an attempt to guarantee the reliability of the data set the following quality assurance conditions were imposed:

1. The borehole is sufficiently deep that the lower section of the temperature-depth profile allows a fairly reliable determination of the deep geothermal gradient, presumably free of the effects of recent climate changes. Order of magnitude calculations indicate that surface temperature changes of the last centuries would penetrate to depths of nearly 150 m, in a medium with a thermal diffusivity of 10^{-6} m^2/s. Thus boreholes of at least 150 m deep are necessary for a reliable determination of the local geothermal gradient. The choice of this depth limit is rather arbitrary since the possibility that low amplitude climate signals of earlier periods are present at larger depths of up to several hundreds of meters cannot entirely be ruled out. However it is a reasonable compromise for examining the GST variations of the last few centuries;

2. The time elapsed between cessation of drilling and the temperature log is at least an order of magnitude large compared to the duration of drilling, minimizing thereby the influence of eventual thermal perturbations generated during the drilling activity;

3. The temperature-depth profile is free from the presence of any significant non-

linear features in the bottom parts of the borehole, usually indicative of advection heat transfer by fluid movements, either in the surrounding formation or in the borehole itself;

4. The elevation changes at the site and in the vicinity of the borehole are relatively small so that the topographic perturbation of the subsurface temperature field at shallow depths is not significant; and

5. The lithologic sequences encountered in the borehole have relatively uniform thermal properties and are of sufficiently large thickness that the gradient changes related to variations in thermal properties does not lead to systematic errors in the procedure employed for extracting the climate related signal.

Out of a total of 129 conventional temperature logs only 16 were found to satisfy the above set of quality assurance conditions. The sites of these selected boreholes are distributed in the states of Santa Catarina, Paraná, São Paulo, Minas Gerais, Rio de Janeiro and Bahia in the eastern parts of Brazil. The geographic distribution of the selected data set is illustrated in the map of Fig. 2.

It must be pointed out that most of the selected data sets have temperature logs with measurements at depth intervals of two meters. Such detailed logs contain valuable information on recent climate changes and also provide more robust estimates of the background temperature gradients. Data from boreholes with depths shallower than 150 m were not considered in the present work in view of the potential uncertainties in the determination of the local undisturbed gradient and consequent difficulties in extraction of the climate signal. On the other hand, information on climate changes of the recent past available in such logs may be used in obtaining qualitative assessment of GST changes.

Information on the locations of borehole sites, elevation, depth ranges of temperature measurements and period of data acquisition are summarized in the set of Tables 1a–1c. In these tables the selected data sets are classified into groups following the three major geographic zones, designated here as subtropical highlands, subtropical humid zones of the interior and of the coastal areas and semiarid zones. Thus, geothermal data for subtropical highland areas are listed in Table 1a, subtropical humid areas of the interior and coastal regions in Table 1b, and semiarid zones in Table 1c. The area extents of these geographic zones are in large part similar to the prevailing climate zones indicated in Fig. 1.

5 Methods employed in data analysis

In the presence of perturbations induced by climate changes the temperature profile at shallow depths of tectonically stable regions may be considered as composed of two parts: a steady state component determined by the flow of heat from the interior of the Earth and a transient component induced by downward propagation of climate related thermal signal induced at the surface. Usually a linear fit to the deeper portion of the log data, where the climate perturbation is practically absent, allows determination of the local temperature gradient. However some care is necessary in selecting the depth interval for determination of the gradient. If the temperature gradient is calculated using a small subset of data from the lowermost part of the borehole its standard deviation (σ_G) is likely to be large as a consequence of the relatively large root mean square (rms) deviation associated with the small number of data points. Progressive inclusion of data from the overlying parts in least square analysis leads to a steady initial decrease in σ_G, as the estimation of gradient becomes more robust. However, as the procedure is continued and more data are included from shallower depths (where non-linear features are present) this tendency is reversed and σ_G increases. In the present work, the depth corresponding to the minimum value of σ_G is considered as indicative of the top of the unperturbed zone. The background gradient determined for the depth interval below this zone was used for calculating the steady component of the temperature field. Subtracting it from the observed temperatures allows determination of the transient component. A similar procedure has also been employed by Roy et al. (2002) in the separation of steady and transient components of temperature profiles in the Indian subcontinent.

The basic theory of the forward modeling methods have been discussed extensively in the literature (Birch, 1948; Cermak, 1971; Vasseur et al, 1983; Lachenbruch et al, 1986, 1988; among others). For the case where surface temperature variation can be represented by a power law relation, analytic solutions are readily available. For example, for a linear (or ramp type) change in surface temperature the relation between the amplitude of the climate signal (ΔT) and the time elapsed (t) at any depth (z) is given by the relation (Carslaw and Jaeger, 1959):

$$\Delta T\ (z) = 4\,\Delta T\, i^2\, erfc\left(z/\sqrt{4\,\kappa\, t}\right) \tag{1}$$

where i^2 erfc is the second integral of the complementary error function and κ the thermal diffusivity of the medium. The best fitting ramp function is obtained by inverting the above relation using iterative procedures such as linearized Newton's method. The iterative procedure for this model, referred to as Ramp Inversion, allows simultaneous determination of the magnitude of surface temperature change and the period of its occurrence. The main limitation of the forward models is that they resolve only for the first-order features in the GST history.

In the inverse problem approach (Tarantola and Valette, 1982) a priori information is not explicitly incorporated in constraining the solution. In addition, it allows consideration of the vertical distribution of thermophysical properties and their uncertainties as model parameters, allowing thereby determination of a more detailed GST history where it is possible to identify also the second order features. The functional space inversion method discussed by Shen and Beck (1991, 1992) and Shen et al. (1992) makes use of the non-linear least squares theory in solving the one dimensional heat conduction equation in a layered half space. The algorithm employed finds the model that minimizes the misfit function:

$$S\,(m) = \frac{1}{2}\ \left\{\ \left[(d - d_0)^t\ C_d\ (d - d_0)\right]\ +\ \left[(m - m_0)^t\ C_m\ (m - m_0)\right]\ \right\} \tag{2}$$

where d and d_0 are respectively the calculated and observed temperatures, m and m_0 the calculated and a priori model parameters and C_d and C_m the covariance matrices of d_0 and m_0. C_d indicates the uncertainty in the observed temperature-depth data while C_m indicates uncertainty in the a priori model. The selection of appropriate values of a priori standard deviations for the temperature (σ_{d0}) and thermal conductivity (σ_{k0}) data are important in determining the solutions. As pointed out by Golovanova et al (2001) the results of ground surface temperature (GST) history, determined by functional space inversion, are sensitive to a priori standard deviations of thermal conductivity. The preferred values for the standard deviations are based on considerations of trade-off between consistency of the solution and data resolution. In the present work we have used 50 mK for standard deviation of the temperature data (σ_{d0}) and 1 W/m K for standard deviation of the thermal conductivity (σ_{k0}).

6 Estimates of surface temperature changes

The vertical distributions of temperatures in boreholes that have passed the selection criteria are illustrated in the set of Figs. 3a–c. As in the case of Table 1 the results are classified into groups for the major geographic zones. Thus, temperature-depth profiles for the subtropical highland areas in the southeastern parts (mainly in the states of São Paulo and Rio de Janeiro) are illustrated in Fig. 3a while those for the subtropical humid zones in the interior and coastal regions are illustrated respectively in Fig. 3b. In a similar manner, temperature-depth profiles for the semi arid zones in the northeast are presented in Fig. 3c. For the sake of clarity in presentation only selected data sets are included in the set of Figs. 3. In addition, some of the temperature-depth profiles in these figures have been shifted laterally to convenient positions along the temperature axis, to avoid overlap and to allow for easy visualization. Consequently, the temperature axes in Figs. display only relative values.

The vertical distributions of temperatures in Figs. 3a–c reveal several remarkable features. For example, the shapes of the temperature depth profiles at shallow depths are consistently concave towards the depth axis, indicative of surface warming events of relatively recent times. The widespread occurrence of such temperature-depth profiles in almost all of the major geographic zones, irrespective of the local geological complexities and changes in soil type, is indication that the observed feature is not related to local processes but generated by a warming event of large spatial dimensions. In this context, it is perhaps significant that temperature profiles with shapes that are convex towards the depth axis, and hence characteristic of cooling events, were not encountered.

The change from transient to steady state thermal regime is found to take place usually in the depth interval of 80 to 150 m. The separation of the steady and transient components of the temperature-depth profiles is an important step in modeling the GST history. As mentioned earlier, the steady state component can easily be estimated from knowledge of the local temperature gradients. In the following sections we present results of both forward and inverse models that provide physically reasonable simulations of the transient components.

6.1 Forward model results

For reasons of brevity we present here results for only the ramp function model. A summary of the results obtained in fitting this model to the observational data discussed in this work is presented in the set of Tables 2a–c. The summary includes magnitudes of the GST change (ΔT) and their duration (t) as well as the values of the rms misfit between the model and the observational data. Also given in Tables 2 are the values of the local geothermal gradient (Γ) and the extrapolated surface temperature (T_0), calculated on the basis of linear fit to the bottom section of the temperature-depth profiles. As before, the results are grouped together for the three major geographic zones.

The results of Tables 2 reveal several notable features. Foremost among these are the distinct differences in the values of mean GST changes between the major geographic zones. For example, the subtropical highland areas seem to be characterized

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by changes in GST in the range of 1 to 3.5°C (Table 2a). The subtropical humid zones of the interior and coastal regions also seem to have nearly similar GST changes (Table 2b). On the other hand, the semiarid zones in the northeast (Table 2c) are characterized by relatively low GST changes, in the interval of 1 to 2°C.

The vertical distributions of such transient components are illustrated in the set of Figs. 4a–c. Note that the magnitudes of the transient components decrease rapidly with depth. At depths greater than 100 m these values fall below the experimental detection limits of temperature changes in boreholes. A closer examination of the results illustrated in Figs. 4 reveals systematic differences in the GST values within individual geographic zones. Consider for example Fig. 4a, which illustrate the vertical distributions of transient components of temperatures for the highland areas in the southeastern parts (in the states of São Paulo and Rio de Janeiro). Relatively low values (less than 1.5°C) are found for localities in the eastern part of this zone (Águas de Lindoia, Serra Negra and Jundiai) while relatively higher values (>1.5°C) are found for those in the western parts (Rafard and Cosmópolis). The primary reason for such intrazonal variations is unknown at the moment, but it seems possible that they are related to microclimatic histories of individual sites. The period of GST change fall in the range of 80 to 150 years. Hence the beginning of the climate change seems to have taken place during the period of approximately 1850 to 1900.

Figure 4b illustrates the vertical distributions of the transient components of temperatures in the interior and coastal regions of the subtropical humid zones. Note that relatively higher values (>1.5°C) are found for localities in the northern parts (Seropédica in the state of Rio de Janeiro and Cachoeiro de Itapemirim in the state of Espirito Santo). This is in contrast with low values (less than 1.5°C) found for localities in the southern states of Santa Catarina and Rio Grande do Sul. The period of climate change is relatively small, in the range of 40 to 100 years. The beginning of the climate change seem to have occurred in the in the time period of 1900 to 1950.

The depth distribution of the transient components for the semiarid zone in northeastern parts of Brazil, illustrated in Fig. 4c, indicate that the magnitude of warming event is relatively smaller, in the range of 1 to 1.5°C. Note the close agreement between the results for the three localities. It is most probably a consequence of the fact that local changes in vegetation cover and soil types have only a minor influence on the surface thermal budget in semi arid zones. Another important feature is that the GST change in this region had its beginning during the time period of 1850 to 1900, significantly earlier than the corresponding periods for other geographic zones.

6.2 Inverse model results

The inverse methods were employed in analysis of temperature-depth profiles for ten localities distributed over the three main geographic zones of Brazil. The criteria used in the selection of profiles included availability of both thermal property data of subsurface layers and supplementary information on the history of changes in the vegetation cover. A summary of the results of inverse modeling is presented in Table 3. The summary includes maximum and minimum values of ground surface temperatures and their respective times of occurrence. Also given in this table are the difference between the maximum and minimum values of GST, the time elapsed between the maximum and minimum and a posteriori estimates of undisturbed GST.

In comparing the GST histories of several localities it is convenient to work with deviations from the site specific mean rather than the absolute value. In the present work GST deviations are calculated by subtracting the model results from the a posteriori estimate of the site specific mean. The results illustrated in the set of Figs. 5a–c, reveal that the ground surface temperatures of these localities have increased by as much as 1 to 3.5°C, over the last century. This observation is in reasonable agreement with the results of the ramp function model discussed in the previous section. However, in all localities the warming events seem to be preceded by cooling episodes occurring over the time period of approximately 1700 to 1900. The amplitudes of the cooling events are much less, falling generally in the range of 0.5 to 1°C. The period prior to 1700 seem to be characterized by near constant temperatures. However, under the current limitations in sensitivity and precision of temperature sensors used for measurements in boreholes, the resolving power of the inversion method is poor for time periods prior to the 17th century. Hence the model results indicating constant temperatures for periods prior to 1700 may not necessarily be representative of true climate history.

The resolving power of the inversion method can somewhat be improved by carrying out simultaneous inversion of temperature profiles of several sites in the same geographical province. In the present work we have carried out simultaneous inversions only for repeat measurements at the site Seropédica in the state of Rio de Janeiro. In view of notable differences in the local soil conditions and vegetation cover, no attempt has been made for carrying out simultaneous inversions of temperature profiles from different locations discussed in the present work. Also, most of these sites are separated by large distances and fall within areas with distinctly different microclimate conditions and geographic characteristics.

A closer examination of the set of Fig. 5 reveals several second order features in the GST history of the main geographic zones. Consider for example the history of GST deviations for the highland areas in the southeastern parts, illustrated in Fig. 5a. Note that surface warming is less intense (less than 1.5°C) in the eastern parts of the state of São Paulo relative to that found in its western parts. The period of warming is also variable, in the range of 80 to 150 years. The GST change seems to have had its beginning in the time interval of approximately 1850 to 1900. Figure 5b illustrates the histories of GST deviations in the subtropical humid regions of the interior and of the coastal areas. In Seropédica, for example, surface warming has been going on during the last 150 years or so. The period prior to 1900 seems to be characterized by cooling event of relatively small magnitude which extends back to several hundred years. The history of GST deviations for the semi arid zone in northeastern parts of Brazil is illustrated in Fig. 5c. It reveals that the magnitude of warming event is relatively smaller, in the range of 1 to 2°C. The beginning of the warming event in this region dates back to the period of 1850 to 1900. Hence the duration of the warming event is relatively larger than that found for the other geographic zones. There is relatively close agreement between the results for the three localities (Arraial, Caraíba and Poço de Fora). This

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is an indication that local small scale changes in soil type and vegetation cover have only a very minor influence in the surface thermal budget of such areas. An important supplementary conclusion is that the climate histories deduced from borehole data in semi-arid zones are indicative of global climate changes, free of perturbations induced by local changes in vegetation cover.

7 Comparison with surface air temperature records

The availability of surface air temperature records of the last century at some of the meteorological stations in Southern Brazil provide an opportunity for an independent check on the history of GST changes inferred from borehole data. There are however several problems in analysis of meteorological records, especially those for the period prior to 1950. Frequent changes in the characteristics of temperature sensors and data acquisition procedures have made it difficult to obtain reasonably long time series with consistent quality characteristics that can be employed in comparative studies. In the present work, we have identified three time series that satisfy the required criteria:

1. Air temperature records for the city of Rio de Janeiro for the period of 1857 to 1866;
2. Air temperature records for the city of Curitiba for the period of 1885 to 1909;
3. Soil temperatures at 40 cm depth at the Meteorological Observatory of São Paulo, for the period of 1965 to 1990.

A preliminary analysis of these data sets was carried out by Hamza (1998). We reproduce here only the results relevant for comparative analysis of GST variations deduced from borehole data. Examination of air temperature records reveal that the short period fluctuations arising from seasonal variations have a dominating influence. In an attempt to minimize this problem seasonally adjusted air temperatures were calculated for data available in the primary records for Rio de Janeiro and Curitiba. The resultant time series are illustrated in Figs. 6a and b respectively. The long term variations determined from these data sets indicate cooling trends of 1.7°C/century for the period of 1857 to 1866 in Rio de Janeiro and 0.4°C/century for the period of 1885 to 1909 in Curitiba. The periods of such cooling trends are in reasonable agreement with those determined from inversion models.

The soil temperatures recorded by the meteorological observatory of the University of São Paulo provides a slightly different picture. To begin with, most of very short period variations are sharply attenuated, since measurements were made 40 cm depth. In taking advantage of this feature, monthly means of soil temperatures were calculated for the period 1965 to 1990. To extract the long term climatic trend the data was fit to a function of the type:

$$T(t) = a + bt + c\cos(2\pi t/P_a) + d\sin(2\pi t/P_a) + e\cos(2\pi t/P_{S1}) + f\sin(2\pi t/P_{S1}) + g\cos(2\pi t/P_{S2}) + h\sin(2\pi t/P_{S2}) \quad (3)$$

where T is temperature, t the time, a the mean annual temperature, b the long term climatic trend, Pa the annual cycle with period of 12 months and P_{S1} and P_{S2} are solar cycles with periods of 11 and 22 years respectively. The least squares fit of Function (3) to the observed data using the SVD (Singular Value Decomposition) method of Press et al. (1986) resulted in the following relation:

$$T(t) = (21.47 \pm 0.12) + (0.00114 \pm 0.00045)\,t + (2.457 \pm 0.007)\cos(2\pi t/P_a) + (2.186 \pm 0.087)\sin(2\pi t/P_a) + 0.970 \pm 0.850)\sin(2\pi t/P_{S1}) \quad (4)$$

The coefficients e, g and h were not included in the final representation since the errors associated with their estimates are large compared with their magnitudes. The multiple correlation coefficient for the fit is 0.91 while the partial correlation coefficient for b is 0.0998. The significance level (S_L) of this value evaluated using the relation:

$$S_L = erfc\left[r \middle/ \sqrt{(N/2)}\right] \quad (5)$$

was found to be 0.09. The non-periodic residuals determined in this manner are shown in Fig. 6c. Unlike the air temperature data the soil temperature residuals point to a long term warming trend of 1.7°C/century, for the time period 1965 to 1990. A summary of long term trends in air and soil temperature records is provided in Table 4.

A comparative analysis of trends observed in geothermal and meteorological records are shown in Fig. 6d. It shows that the cooling and warming trends inferred from meteorological records are in reasonable agreement with the results obtained in the present work.

8 Discussion and conclusions

The results obtained in the present work indicate that surface temperatures have increased during the last century in most of the major geographic zones of eastern Brazil. Magnitudes of the GST changes are in the range of 1 to 3.5°C while their durations are found to fall in the interval of 50 to 150 years. The occurrence of such changes in regions of large area extent and of differing vegetation cover imposes severe constraints on the possible mechanisms involved. Another notable feature of GST variations in Brazil is that the recent warming trend is preceded by a cooling episode with magnitudes of less than 1°C, during the 17th and 18th centuries. Similar cooling episodes have also been identified in several regions of Europe and North America (Golovanova et al., 2001; Safanda and Rajver, 2001; among others).

Results of the present work also indicate that the history of changes in vegetation cover have marked influence on GST variations. Thus the magnitudes of observed GST changes are relatively large in localities where the original vegetation cover has been removed. A similar conclusion was also reached by Cerrone and Hamza (2003) in comparing contour maps of GST changes for the state of Rio de Janeiro with satellite images of vegetation cover. The role of vegetation cover in controlling GST changes has also been noticed in the earlier works by Lewis and Wang (1988) and Rimi (2000).

Another important point emerging from the results of the present work is that the magnitudes of surface warming are relatively small in semi-arid zones of northeast Brazil where vegetation cover is sparse. The reduced influence of vegetation cover implies that GST history deduced from borehole data in semi-arid zones are representative of global climate changes.

There is very little information at present on GST changes for the northern tropical region of Brazil. Souza et al. (1991) reported results of temperature logs of three shallow bore holes in the city of Belém (northern State of Pará) and three more in Manaus (state of Amazon). Details of this data are not reproduced here, being not fully compatible with the quality criteria of the present work. Nevertheless, the absence of non-linear features in temperature logs at shallow depths of less than 100 m in these localities indicates that GST changes are relatively small or altogether absent in areas of thick vegetation cover. It is well-known that thick vegetation cover of tropical regions (such as rain forests) has a strong control on thermal energy budget of the near surface soil layers. One possible explanation is that such vegetation cover blanket GST from the perturbing effects of air temperature changes. Consequently, the subsurface temperatures in tropical forest areas are likely to be less immune to climate changes.

In summary, it appears that the observed subsurface temperature variations in semi-arid regions and tropical rain forests represent extreme or end-member cases of large scale GST changes. According to this interpretation the observed GST changes in the subtropical regions in the southern and southeastern parts of Brazil are representative of intermediate cases which include components related to changes in both global climate and local vegetation cover.

Lack of reliable data for the central and northern parts is a limitation in understanding the geographic distribution of GST in continental area of Brazil. Nevertheless, the present data set has been employed in deriving mosaic and contour representations of regional trends in recent GST changes for areas of low data density. The results reveal that GST changes are prominent in the southern and southeastern parts and moderate in the northeastern region. This observation is in reasonable agreement with the conclusions by Hamza (1998) that GST changes are less pronounced in Equatorial relative to Polar Regions.

Finally a brief comment of the similarities and differences between GST changes observed in Brazil with those reported for other continental regions is in order. The GST changes reported for USA (Gosnold et al., 1997), western Canada (Majorowicz and Safanda, 2001), Urals (Golovanova et al., 2001) and southwest China (Huang et al., 1995) were selected for this purpose. A simple comparison of GST changes reported for these regions with those observed for Brazil is illustrated in Fig. 7. Note that the warming trend of the last century observed for most localities in Brazil are similar to the GST changes reported for corresponding periods in the northern hemisphere. However, for the period of 1700 to 1900, the observed GST variations in Brazil seem to have systematically lower magnitudes than those reported for other continental areas.

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Table 1a. Basic data on temperature-depth profiles selected for climate studies in Subtropical Highland areas of Brazil. The references are: 1- Del Rey (1986); 2- Del Rey and Hamza (1989); 3- Araujo (1978); 4- Cerrone and Hamza (2003); 5- Gomes (2004); 6- Gomes and Hamza (2005).

Borehole	Locality	S. Latitude/ W. Longitude	Depth (m)	Log Year	References
AL-1	Águas de Lindóia	22°29′ 46°38′	200	1982	1, 2
AM-1	Amparo	22°43′ 46°46′	204	1982	1, 2
CO-1	Cosmópolis	23°43′ 47°12′	210	1982	1, 2
IT-1	Itu	23°15′ 47°19′	177	1982	1, 2
JD-1	Jundiai	23°10′ 46°52′	172	1982	1, 2
RF-1	Rafard	23°00′ 47°31′	194	1982	1, 2
SN-1	Serra Negra	22°36′ 46°32′	184	1982	1, 2
PC-1	Poços Caldas	21°55′ 46°25′	214	1976	3

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Table 1b. Basic data on temperature-depth profiles selected for climate studies in the Sub-tropical Humid areas of Brazil. The references are: 7- Hamza et al. (1978); 8- Vitorello et al. (1978).

Borehole	Locality	S. Latitude/ W. Longitude	Depth (m)	Log Year	References
CI-1	Cachoeiro Itapemirim	19°06′ 41°04′	160	1975	7, 8
PP-1	Papanduva	26°23′ 50°08′	180	2000	7, 8
LP-1	Seropédica	22°45′58″ 43°39′15″	300	2001, 2003	4, 6
SR-9	São Sebastião	23°48′ 45°25′	188	1991	9

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Table 1c. Basic data on temperature-depth profiles selected for climate studies in the Tropical Semi Arid zones of Brazil. The references are: 7- Hamza et al. (1978); 8- Vitorello et al. (1978).

Borehole	Locality	S. Latitude/ W. Longitude	Depth (m)	Log Year	References
AR-1	Arraial	12°32′ 42°50′	169	1976	7, 8
CA-1	Caraiba	09°28′12″ 39°50′09″	511	1976	7, 8
CA-2	Caraiba	09°28′12″ 39°50′09″	300	1976	7, 8
PF-1	Poço de Fora	09°41′20″ 39°51′20″	230	1976	7, 8

Table 2a. Results of Ramp Inversions for surface temperature changes, for localities in Sub-tropical Highland areas. Γ is the local geothermal gradient, T_0 the intercept of linear fit, ΔT the magnitude of ramp change, and r the root mean square misfit.

Locality	Γ (°C/km)	T_0 (°C)	ΔT (°C)	Time (year)		r (mK)
				Duration	Onset	
Águas de Lindóia	19.9	18.4	3.2	105	1877	4.4
Amparo	18.3	18.8	2.8	115	1852	5.5
Cosmópolis	28.8	20.0	3.8	75	1907	5.5
Itu	18.5	19.6	1.2	60	1922	3.2
Jundiaí	20.2	18.7	1.2	50	1932	7.2
Rafard	23.4	18.9	3.8	60	1922	6.8
Serra Negra	24.2	18.3	2.0	105	1877	3.9
Poços Caldas	33.4	18.2	2.0	50	1926	13.7

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Table 2b. Results of Ramp Inversions for surface temperature changes, for localities in Subtropical Interior areas. Γ is the local geothermal gradient, T_0 the intercept of linear fit, ΔT the magnitude of ramp change, and r the root mean square misfit.

Locality	Γ (°C/km)	T_0 (°C)	ΔT (°C)	Time (year)		r (mK)
				Duration	Onset	
C. Itapemirim	12.6	20.7	3.6	65	1910	14.1
Papanduva	26.0	16.6	1.2	90	1885	15.0
Cachoeira do Sul	10.4	21.2	1.8	70	1905	12.0
Seropédica	22.4	21.8	3.8	145	1860	23.1
São Sebastião	14.3	21.2	2.6	70	1920	23.1

Table 2c. Results of Ramp Inversions for surface temperature changes, for localities in Semi Arid areas. Γ is the local geothermal gradient, T_0 the intercept of linear fit, ΔT the magnitude of ramp change, and r the root mean square misfit.

Locality	Γ (°C/km)	T_0 (°C)	ΔT (°C)	Time (year)		r (mK)
				Duration	Onset	
Arraial (BA)	12.4	27.6	1,4	85	1890	8,4
Caraiba 1 (BA)	14.9	28.9	1,4	110	1865	9,3
Caraiba 2 (BA)	10.1	28.9	2,0	125	1850	8,4
Poço de Fora (BA)	20.6	28.4	2,2	105	1870	4,9

Table 3. Results of functional space inversion for selected data sets. Maximum and minimum values of GST and their respective years of occurrences are given in columns 3–6. Also given are the differences between the maximum and minimum (D) and the time elapsed between the maximum and minimum (t). T_0 is the a posteriori steady state temperature.

Geographic Zone/Climate Province	Locality	Maximum		Minimum		Difference		T_0 (°C)
		°C	Yr	°C	Yr	D (°C)	t (yr)	
Subtropical Highlands	Amparo	21,1	1949	18,1	1802	3,0	147	18,9
	Itu	20,7	1982	19,4	1920	1,3	62	19,9
	Jundiai	21.7	1984	17.6	1821	4.0	163	18.3
	M. Alegre	21.4	1968	17.9	1876	3.5	92	18.7
Subtropical Interior	Itapemirim	23,7	1971	20,0	1883	3,7	88	21,2
	Seropédica	25.3	1979	21.9	1860	3.4	119	22.5
Coastal Area	Campos	25,7	1999	22,7	1936	3,0	64	23,9
	Arraial	28,8	1967	27,2	1863	1,6	104	27,7
Semiarid	Caraíbas	30,1	1946	28,6	1812	1,6	134	29,0
	Poço Fora	30,4	1976	28,2	1822	2,1	154	28,7

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Table 4. Summary of long term trends in air and soil temperature records. N is number of data.

Locality	Period	Data Type	N	Trend (˚C/yr)
Rio de Janeiro	1857–1866	Surface air temperature	85	–0.017
Curitiba	1885–1909	Surface air temperature	289	–0.004
São Paulo	1965–1990	Soil temperature	294	+0.017

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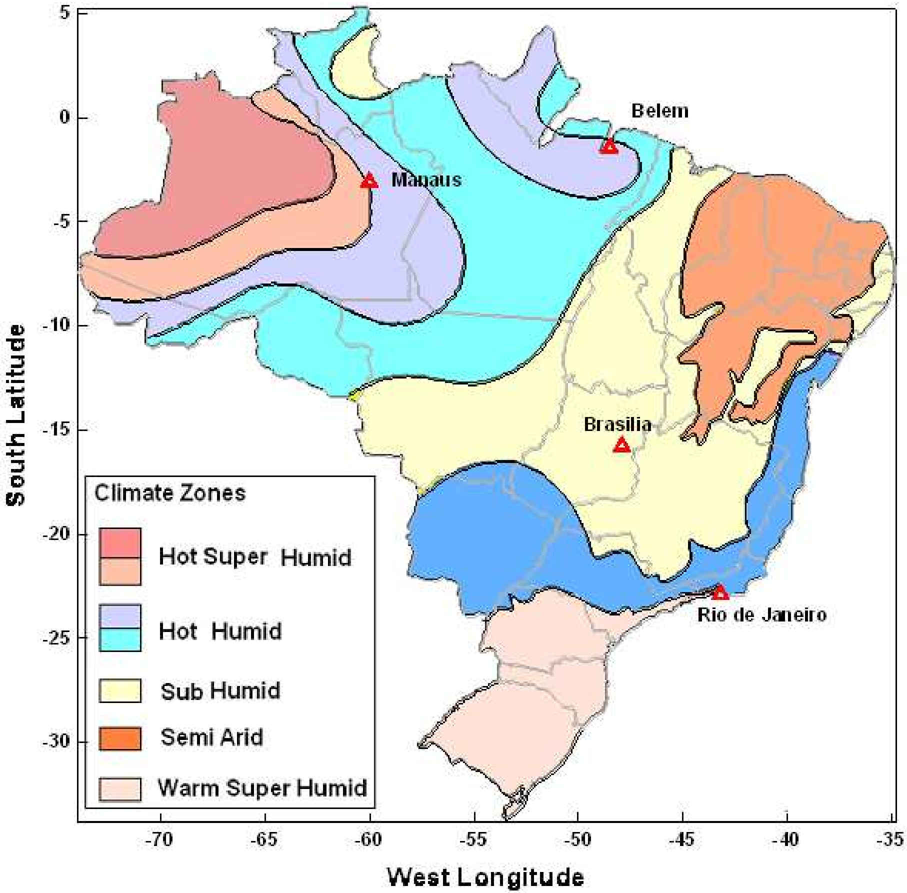

Fig. 1. The prevailing climate zones of Brazil. Adapted with modifications from IBGE (http://www.ibge.org.gov.br) and INMET (2003).

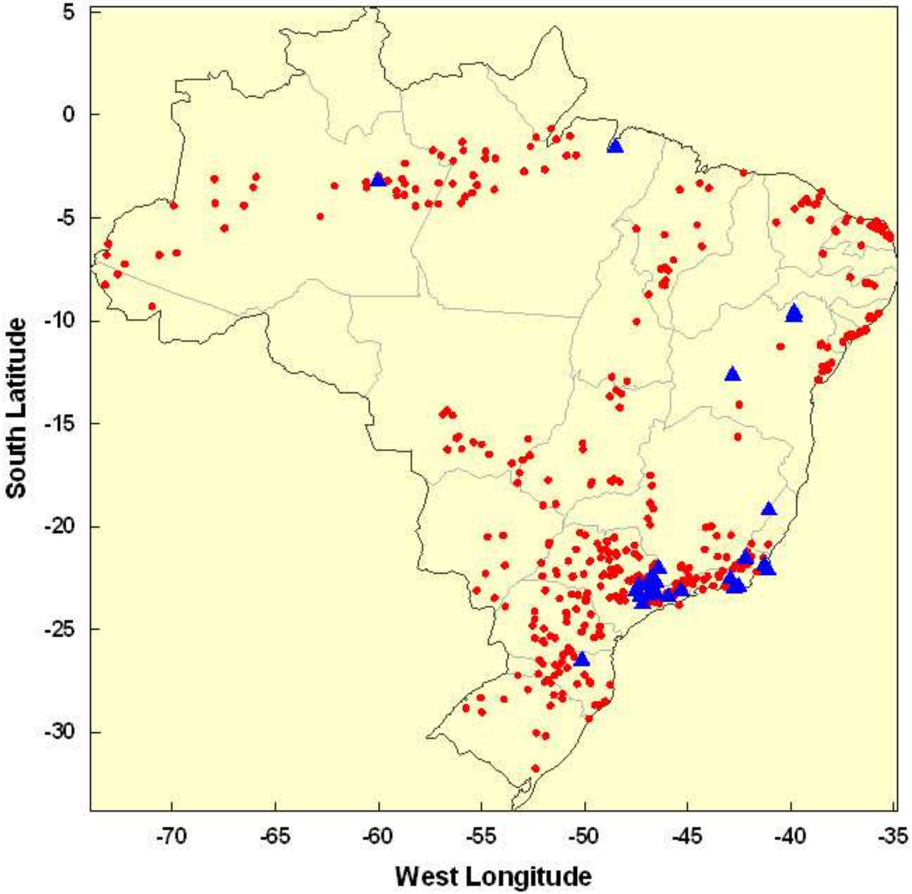

Fig. 2. Locations of geothermal measurements (solid circles) and data sets selected for climate studies (solid triangles) in Brazil.

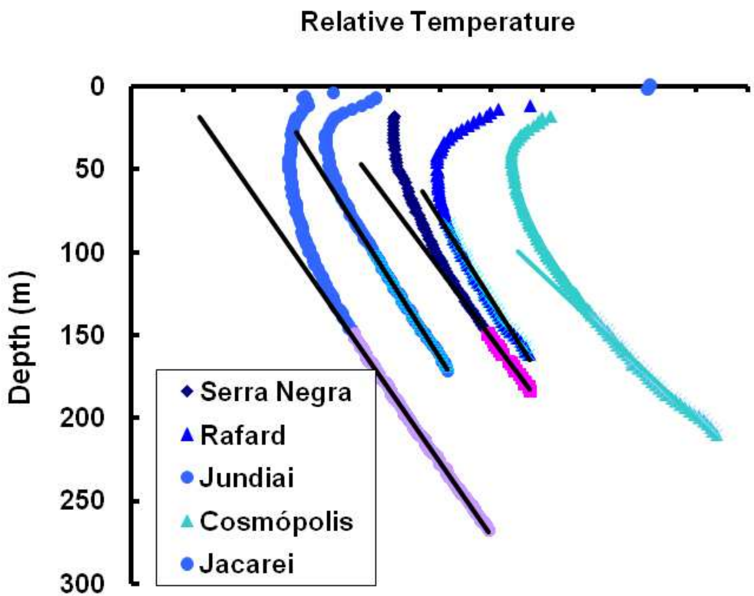

Fig. 3a. Temperature-depth profiles of boreholes situated in the subtropical highlands region of southeast Brazil. For the sake of clarity in presentation only selected data sets are included. In addition, some of the temperature-depth profiles are shifted to convenient positions to avoid overlap.

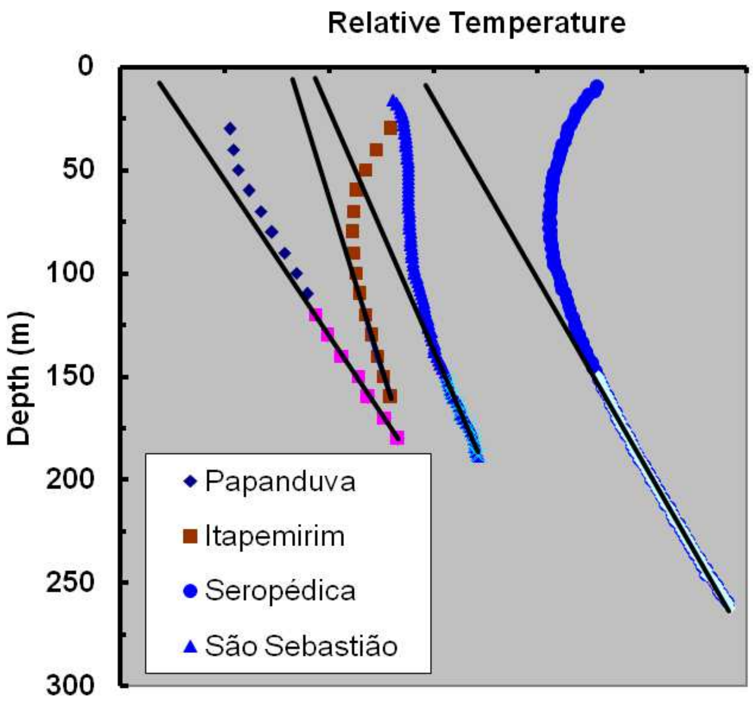

Fig. 3b. Temperature-depth profiles of boreholes situated in the subtropical humid interior regions of southern and southeastern Brazil. Note that some of the temperature-depth profiles have been shifted to convenient positions to avoid overlap.

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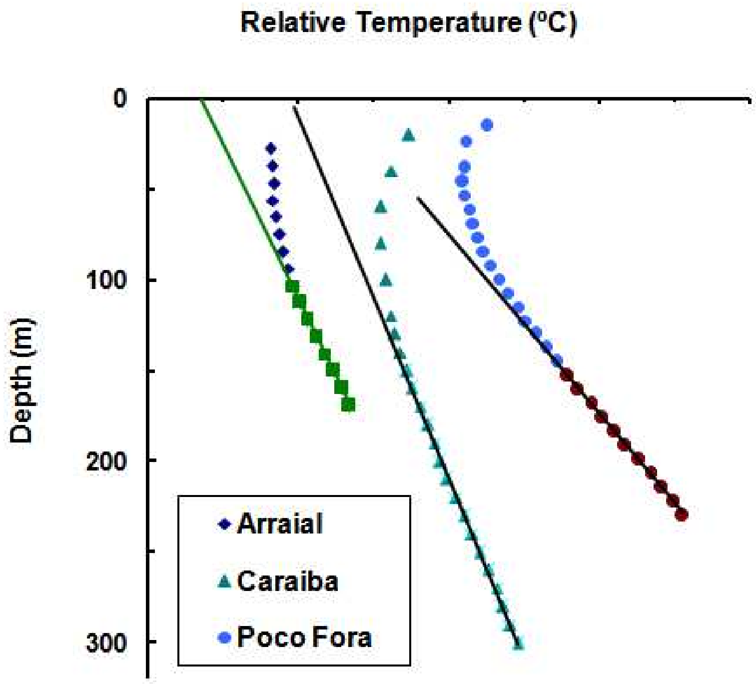

Fig. 3c. Temperature-depth profiles of boreholes situated in the semiarid zones of northeast Brazil. Note that some of the temperature-depth profiles have been shifted to convenient positions to avoid overlap.

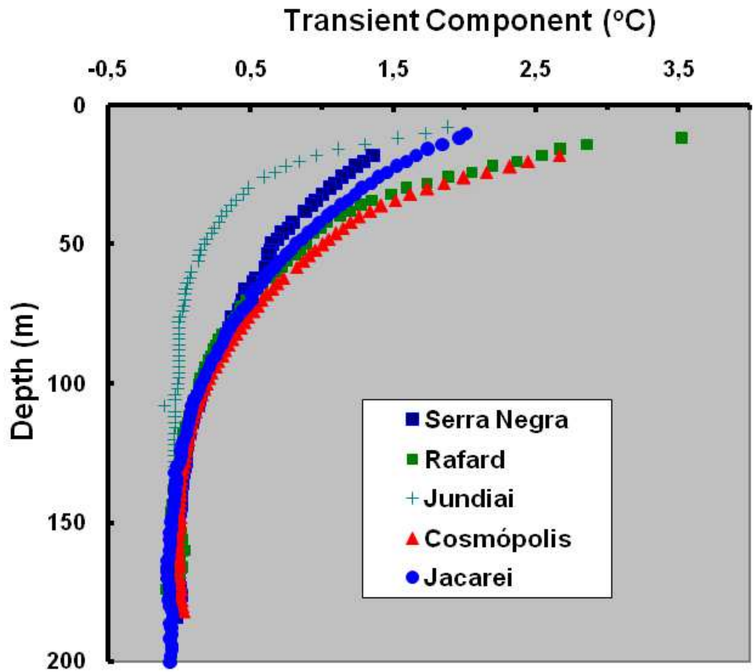

Fig. 4a. Vertical distributions of the transient components of subsurface temperatures in the subtropical highlands region of southeast Brazil. Note that only selected data sets are included.

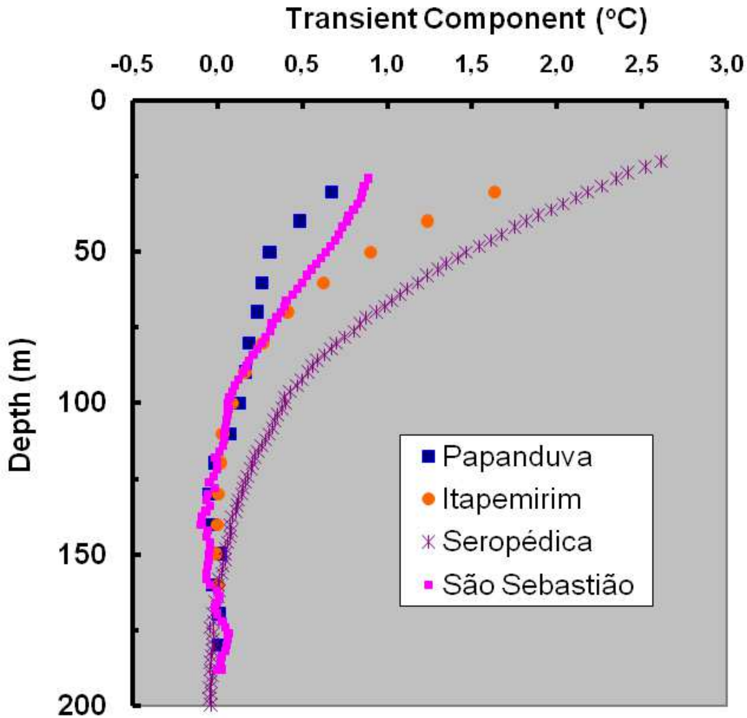

Fig. 4b. Vertical distributions of the transient components of subsurface temperatures in the subtropical humid interior regions of the southern and southeastern Brazil. Note that only selected data sets are included.

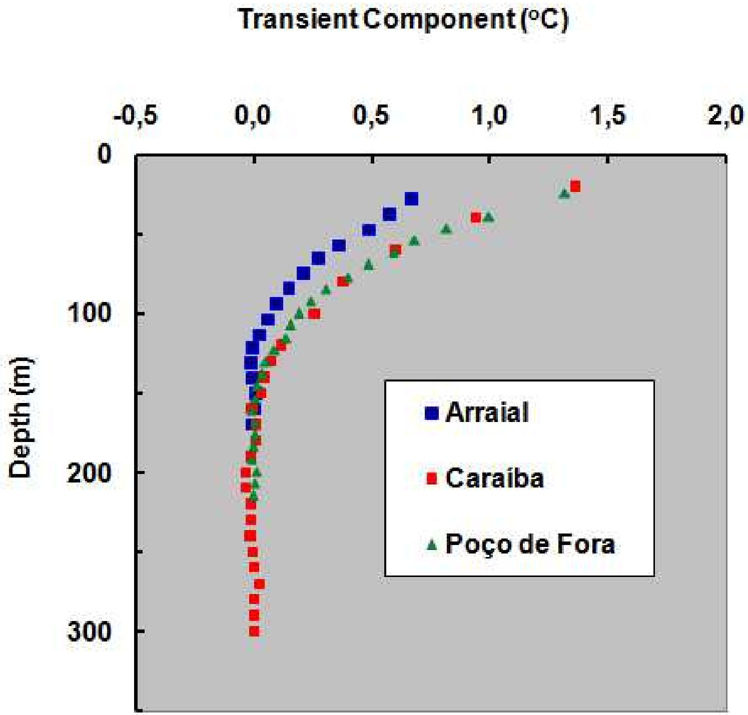

Fig. 4c. Vertical distributions of the transient components of subsurface temperatures in the semiarid zones of northeastern Brazil. Note that only selected data sets are included.

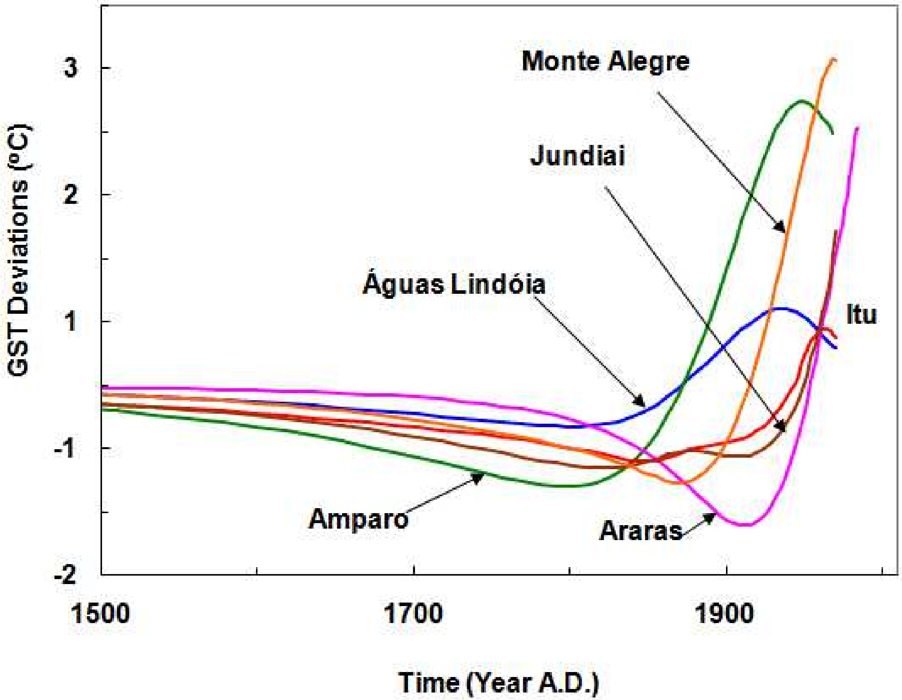

Fig. 5a. Transient ground surface temperature changes derived from inverse models of temperature-depth profiles for the subtropical highlands region of southeast Brazil.

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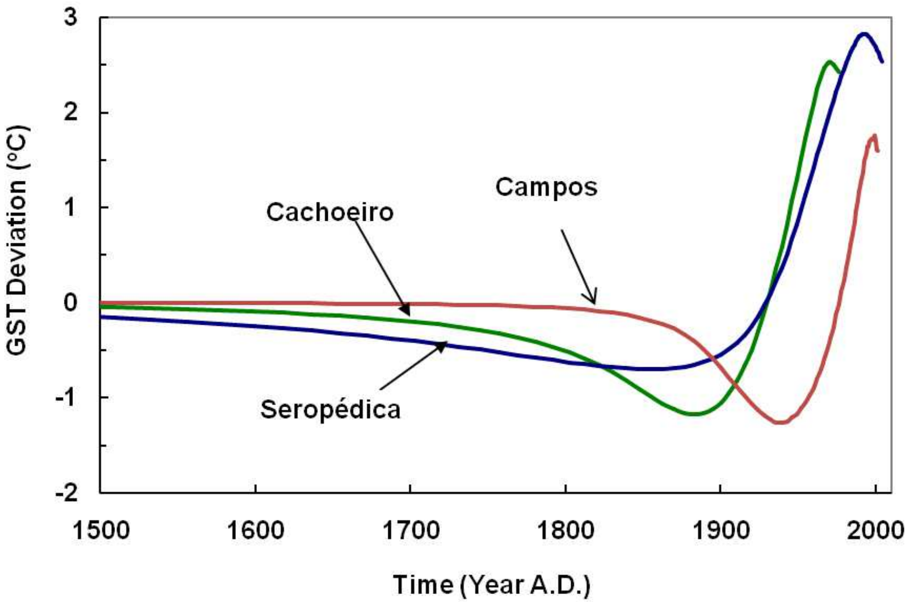

Fig. 5b. Transient ground surface temperature changes derived from inverse models of temperature-depth profiles for the subtropical humid interior regions of southern and south-eastern Brazil.

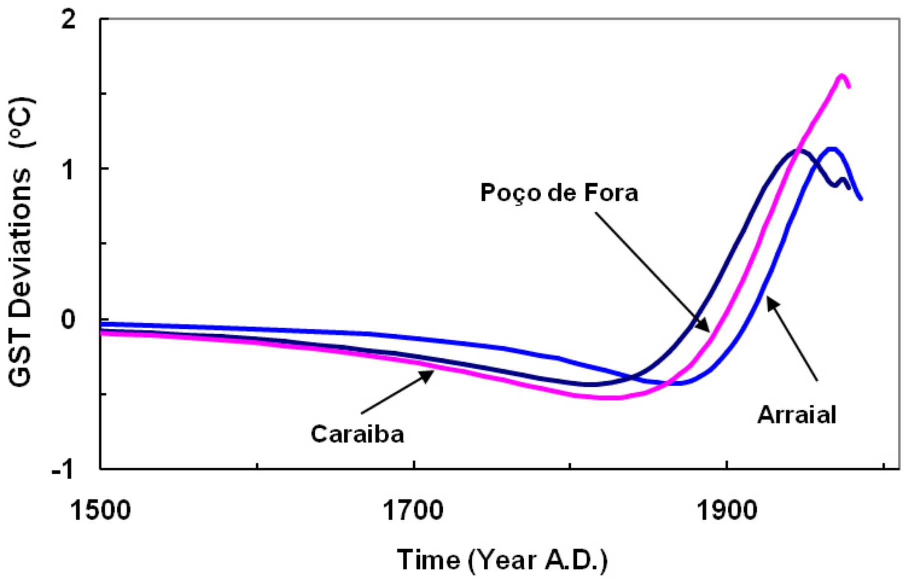

Fig. 5c. Transient ground surface temperature changes derived from inverse models of temperature-depth profiles for the semiarid regions of northeastern Brazil.

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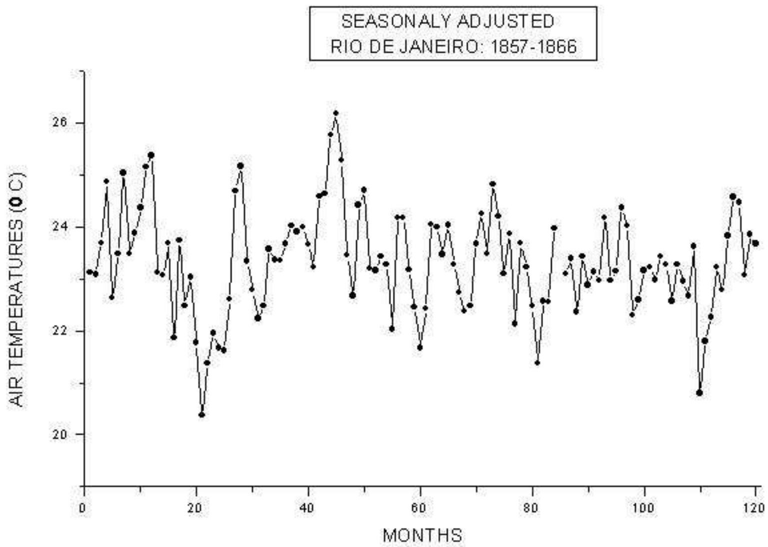

Fig. 6a. Seasonally adjusted values of surface air temperatures, calculated from data furnished by the meteorological observatory in Rio de Janeiro. The long term trend for this time series is 1.7°C/century, for the time period of 1857 to 1866.

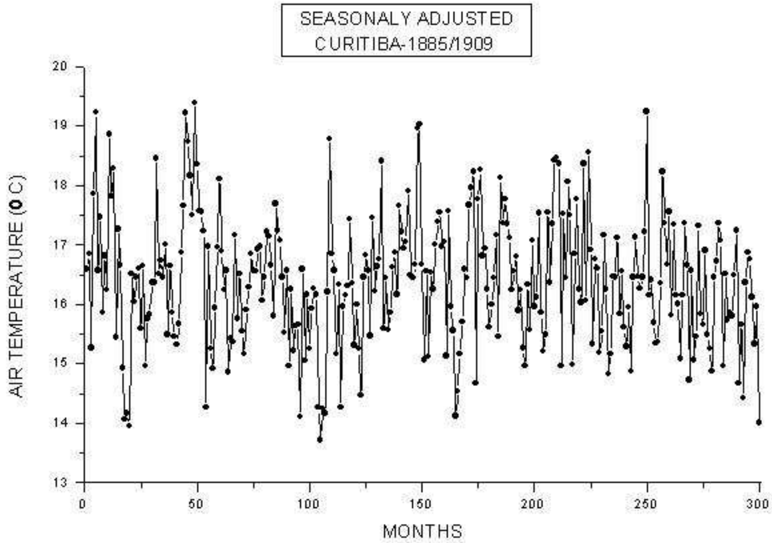

Fig. 6b. Seasonally adjusted values of surface air temperatures, calculated from data furnished by the meteorological observatory in Curitiba. The long term trend for this time series is 0.4°C/century, for the time period of 1885 to 1909.

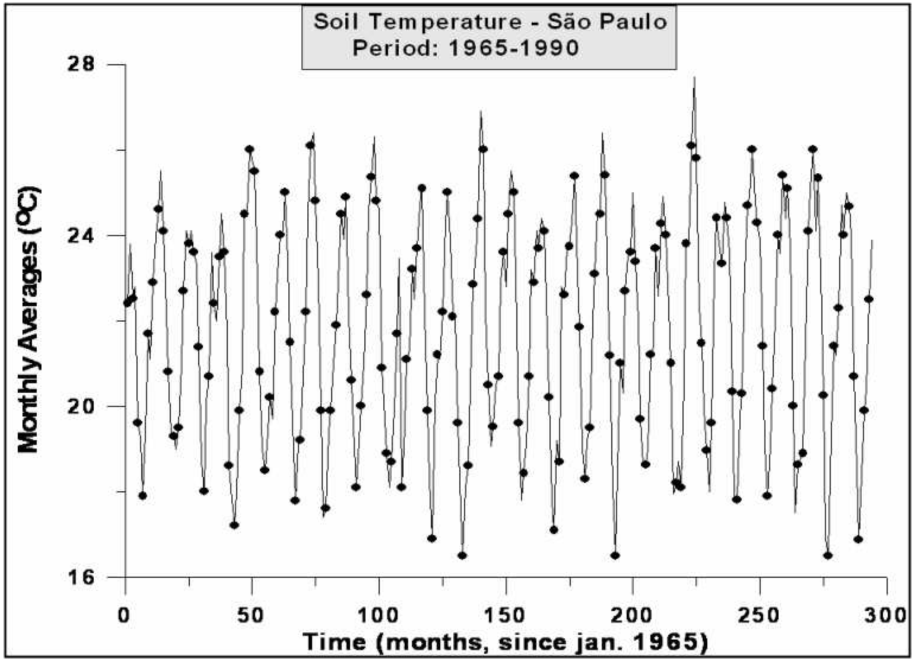

Fig. 6c. Monthly means of soil temperatures at 40 cm depth, calculated from data furnished by the meteorological observatory in São Paulo. The long term trend for this time series is 1.7°C/century, for the time period of 1965 to 1990.

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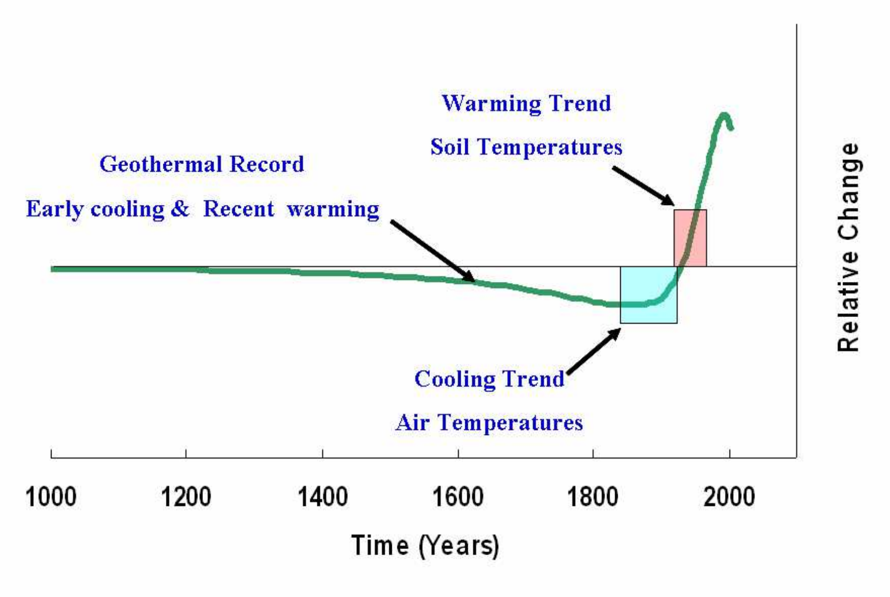

Fig. 6d. Illustration of warming and cooling trends identified in geothermal profiles and its comparison with those observed in surface air and soil temperature records of meteorological stations.

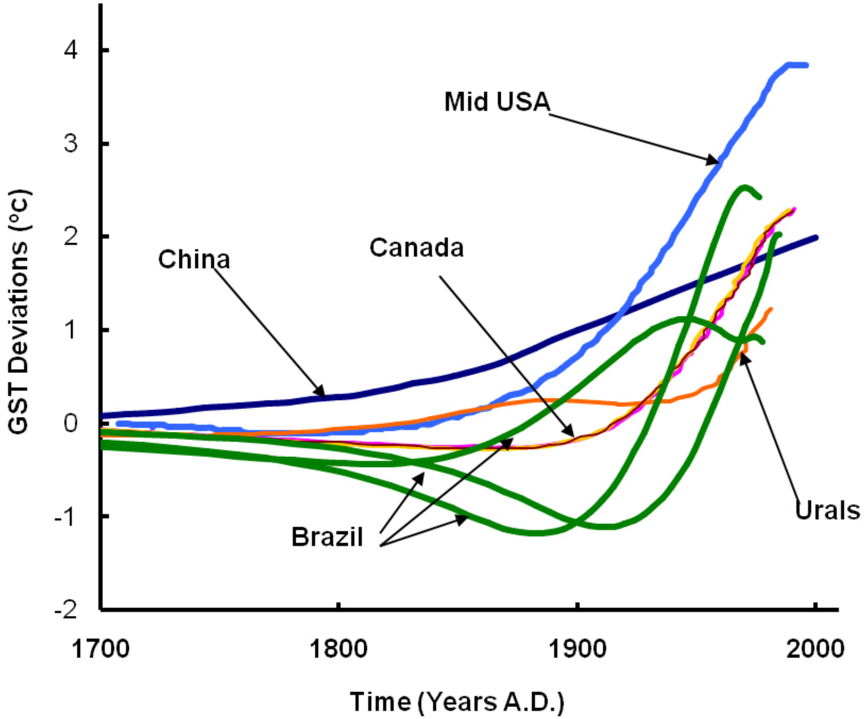

Fig. 7. Comparison of GST deviations observed in Brazil with those reported for Mid-continent USA, Canada, Southwest China and the Urals. Note that all regions are characterized by pronounced warming trends in GST during the last century.

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